Soil Organic Carbon Sequestration Potential of Adopting Conservation Tillage in U.S. Croplands

R.R. Allmaras, H.H. Schomberg, C.L. Douglas Jr., and T.H. Dao

ABSTRACT: Soil organic carbon (SOC) makes up about two-thirds of the C pool in the terrestrial biosphere; annual C deposition and decomposition to release carbon dioxide (CO_2) into the atmospheric constitutes about 4% of this SOC pool. Cropland is an important, highly managed component of the biosphere. Among the many managed components of cropland are the production of crop residue, use of tillage systems to control crop residue placement/disturbance, and residue decomposition. An accumulation of SOC is a C sink (a net gain from atmospheric CO_2) whereas a net loss of SOC is a C source to atmospheric CO_2. A simple three components model was developed to determine whether or not conservation tillage systems were changing cropland from a C source to a C sink. Grain/oil seed yields and harvest indices have indicated a steadily increasing supply of crop residue since 1940, and long term field experiments indicate SOC storage in no-tillage > non moldboard tillage > moldboard tillage systems. According to adoption surveys, moldboard tillage dominated until about 1970, but non moldboard systems are now used nationally on at least 92% of planted wheat, corn, soybean, and sorghum. Consequently, since about 1980, cropland agriculture has become a C sink. Moldboard plow systems had prevented a C sink response to increases in crop residue production that had occurred between 1940 and 1970. The model has not only facilitated a qualitative conclusion about SOC but it has also been used to project production, as well as soil and water conservation benefits, when a C credit or payment to farmers is associated with the C sink in cropland agriculture.

Keywords: Crop residue, C pool, soil organic carbon, tillage systems

The soil organic carbon (SOC) pool is estimated to be about two-thirds of that in the terrestrial biosphere C pool, and the estimated annual exchange is about 4% of the SOC pool, or 8–11% of the atmospheric pool (Schlesinger 1995). This SOC pool is viewed as a potential carbon (C) sink for atmospheric carbon dioxide (CO_2) and is estimated to have a half life of about 32 years. Cropland makes up about 20% of the terrestrial biosphere in the U.S. Summerfallow and harvested continuous crops make up about 70% of the cropland (Lal et al. 1999) to include areas with cover crop production. Components of the SOC pool in cropland have a wide range of susceptibility to decomposition, in other words, half lives from < 1 to > 1000 years (Schlesinger 1995). Cropland is an important component of C sink

management because it is intensively managed with tillage, crop residues, biomass importation (manures), and fertilizers to produce large amounts of grain and fiber (exported biomass). Herein lies a new challenge for conservation tillage.

The SOC pool in croplands converted from grasslands was reduced as much as 40% to reach a near steady low state by about 1940; conversion of grasslands to cropland had already ceased in 1910 when crop yields were stagnantly low (Allmaras et al. 1998). In the eastern U.S. where deciduous forests were converted to cropland early in the nineteenth century, land was cleared for cultivation and then abandoned back to forest when crop yields declined (Paustian et al. 1997), but later in the nineteenth century there was more forage and legume production, along with biomass importation. Cotton production during the nineteenth century in the cleared forests of the southeastern U.S. produced soil erosion sufficient to devastate landscapes and crop production (Bruce and Langdale 1997). Total cropland in the U.S. grew about 10% from 1910 until about 1970, but has decreased since to about 134 million ha (331 million ac), with little change since 1980.

To recover about 50% of the maximum SOC, Lal et al. (1999) suggest conservation based production practices for an attainable C sink. This renewed SOC storage may range to about 10% of the increased atmospheric CO_2 due to anthropogenic combustion of fossil fuels. Components of an increased SOC storage are an increased C input via plant biomass production and a decreased C loss to CO_2 via improved practices to suppress decomposition of soil organic matter.

Estimates of practices to maximize the C sink and how these practices relate to international conventions to reduce greenhouse gases are discussed by Lal et al. (1999) and Bruce et al. (1999). This paper discusses how tillage and crop residue management in the U.S. may have moved SOC storage from a C source to a C sink. Our research used a model consisting of three elements: 1.) progress since 1910 to increase and somewhat stabilize sources of biomass available to enter the SOC sink, 2.) SOC storage depending on crop residue input and tillage system control on placement/disturbance of crop residues, and 3.) changes in adopted tillage systems.

Plant Biomass as Crop Residues

Temporal trends in the harvested yield of 10 crops show a steady increase since 1930 (Table 1). The trend is a continuation of focus on food production and a solvent agriculture since 1870 (Allmaras et al. 1998). Net primary production of plant biomass available for soil organic matter improvement, plant nutrient management, and soil erosion control did not receive public attention until there was an interest in crop residues for biofuels (Larson 1979).

Until about 1940, most cropland was tilled with a moldboard plow after grain harvest (an exportation of biomass). Crop residue was moved to a central point in the field or removed from the field using labor intensive harvest methods, some crop residue was used for livestock feed and bedding, and very little fertilizer was used to replace/restore the harvested nutrients. Intensive tillage and black fallow were used for weed control, mineralization of nutrients (especially nitrogen), and soil water storage. Consequently, SOC levels in tallgrass prairie soils decreased as much as 60% (Huggins et al. 1998). Decreases were often 20–40% in semiarid lands (Janzen et al. 1998; Peterson et al. 1998). These SOC losses had not received public attention until long

Raymond R. Allmaras is a soil scientist with the USDA-ARS in the Department of Soil, Water, and Climate at the University of Minnesota. Harry H. Schombert is a soil scientist with the USDA-ARS in Watkinsville, Georgia. Clyde L. Douglas is a soil scientist with the USDA-ARS in Pendleton, Oregon, and Thang H. Dao is a soil scientist with the USDA-ARS in Beltsville, Maryland.

Table 1. Yields of ten crops for selected years during the period from 1930 to 1990 (adopted from Allmaras et al. 1998)[a].

Year	Barley	Oat	Corn	Sorghum	Soybean	Sunflower	Wheat	Cotton	Potato	Hay
				kg ha⁻¹					t ha⁻¹	

Year	Barley	Oat	Corn	Sorghum	Soybean	Sunflower	Wheat	Cotton	Potato	Hay
1930	1140	1090	1500	880	940	—[b]	990	200	7.5	2.6
1935	1070	880	1190	670	1050	—	840	210	7.6	2.5
1940	1280	1150	1890	930	1260	—	1050	280	8.8	2.9
1945	1340	1220	2180	1080	1310	—	1180	300	11.1	3.1
1950	1430	1260	2380	1370	1480	—	1070	310	16.5	3.2
1955	1560	1310	2650	1960	1410	—	1330	440	19.9	3.4
1960	1640	1500	3540	2540	1650	—	1640	510	21.4	3.9
1965	2170	1680	4470	3170	1660	—	1790	580	23.2	4.2
1970	2430	1930	5240	3370	1860	1099	2180	500	25.8	4.8
1975	2380	1730	5240	3050	1790	1190	2010	520	29.0	4.8
1980	2790	1960	6580	3680	2020	1350	2330	570	30.9	5.3
1985	2830	2160	7320	4060	2180	1330	2530	680	33.2	5.6
1990	2920	2010	7310	3790	2290	1360	2430	720	33.7	5.4

[a] Three year average centered on the year indicated. Crops with botanical names are: barley (*Hordeum valgare* L), oat (*Avena sativa* L), corn (*Zea mays* L), sorghum (*Sorghum bicolor* L), soybean (*Glycine max* L Merrill), sunflower (*Helianthus annus* L), wheat (*Triticum spp.*), cotton (*Gossypium hirsutem* L), and potato (*Solanum tuberosum* L).

term field studies quantified SOC changes due to tillage and residue management treatments (Rasmussen et al. 1998b), and concerns were expressed about increased atmospheric CO_2 linked to global warming (CAST 1992).

Yields of harvested biomass (Table 2) have increased in the range of 75–400% from 1940 to 1990; this increase can be attributed to chemical, biological, and mechanical technologies (Allmaras et al. 1998). Root and hay crops followed the same intensity of harvest increase as for grain and oil seed crops (Table 1). The harvest index (HI = harvested biomass + total aboveground biomass, including that to be harvested) of six selected grain and oil seed crops has increased about 45% in response to genetic technology. However, crop residue production increases in response to increased harvestable biomass and HI changes, ranges from 15% for small grains to100% for corn and sorghum (Table 2).

Most of the HI changes had already occurred before 1980, but increases in net primary production have also occurred since 1980, some of which are plant growth responses to increased atmospheric CO_2 (Rogers et al. 1994). The HI (Table 2) also shows the burden of exported net primary production inherent in crop production, which contributed to early declines in SOC and emphasized the need for high current production to maintain an ample supply of crop residues. Some long term field experiments (e.g., Huggins et al. 1998) showed a small increase of SOC around 1950 when improved harvesting technology began to remove only the grain. This

Table 2. Grain yield, harvest index, and crop residue production for seven selected crops over the 1940–1990 period, averaged for the United States (adopted from Allmaras et al. 1998).

Crop	Grain yield		Harvest index		Crop residue	
	1940	1990	1940	1990	1940	1990
	kg ha⁻¹				kg ha⁻¹	
Barley	1280	2920	0.27	0.40	3460	4380
Corn	1890	7310	.35	.50	3510	7310
Oat	1150	2010	.23	.32	3850	4270
Sorghum	930	3790	.34	.50	1800	3790
Soybean	1260	2290	.30	.35	2940	4250
Sunflower	—[a]	1500	—	.33	—	2760
Wheat	1050	2430	.28	.45	2700	2970

[a] No data reported.

change had already occurred earlier in the semiarid croplands (Allmaras et al. 1998). Earlier harvest methods had a larger HI because they removed much of the shoot for threshing/shelling and did not return this residue to the point of harvest (Allmaras et al. 1998).

Grain and oil seed production, along with HI, were used to estimate the C available in crop residue (Table 3 "shoot only"). Carbon present in the "root plus shoot" was conservatively estimated using a root:shoot ratio of 0.2 x total biological yield of the shoot, including the portion to be harvested, as recommended by Beauchamp and Voroney (1994). This ratio depends on the crop and should be larger than 0.2 because rhizodeposition and exudation can make up at least 50% of the C allocated belowground (Swinnen et al. 1994; Bolinder et al. 1997). Measured root:shoot ratio can vary from 0.16 (Balesdent and Balabane 1992) to 0.55 (Buyanovsky and Wagner 1986) in corn,

Table 3. Estimated changes (1940–1990) in carbon available in crop residue for return to the soil (adopted from Allmaras et al. 1998).

Crop	Shoot only[a]		Root plus shoot[b]	
	1940	1990	1940	1990
	C, kg ha⁻¹			
Barley	1380	1750	1760	2340
Corn	1400	2920	1840	4090
Oat	1540	1710	1940	2210
Sorghum	720	1520	940	2120
Soybean	1180	1700	1510	2040
Sunflower	—	1100	—	1430
Wheat	1080	1190	1380	1620

[a] Estimated 40% C content of crop residue; does not include harvested grain or oil seed.
[b] Root biomass estimated to be 20% of shoot biomass including harvested grain.

and 0.29 (Keith et al. 1986) to 0.40 (Rasmussen et al. 1998b) in wheat. Soybeans can have a root:shoot ratio as large as 0.57 (Buyanovsky and Wagner 1986).

The "root plus shoot" input of C has increased from 45–125% since 1940 for six of the crops listed (Table 3), and the range of input C among crops in 1990 is as much as 115% of the mean among crops. Buyanovsky and Wagner (1986) measured HI about 30% lower than estimated in Table 2 for corn, wheat, and soybeans— this lower estimate indicates that the estimated "root plus shoot" return of C in Table 2 likely underestimates the C available to build a C sink. Root:shoot ratio alone can be misleading because recalcitrance of corn root tissue is about 1.5 times that of the "root plus shoot" tissue (Balesdent and Balabane 1996).

Tillage System Influences on Soil Organic Carbon Storage

Many long term field trials have shown that the moldboard tillage system has SOC storage inferior to all other tillage systems, including no-tillage and non moldboard tillage systems that have primary tillage with chisels, disks, sweeps, shovels, and tines. Involved were comparisons between no-tillage with moldboard, no-tillage with non moldboard tillage, and moldboard tillage systems. Within a field trial, SOC is expressed as mass of C per unit area within a soil depth determined by the deepest tillage. In only five of the 25 comparisons between no-tillage and moldboard based systems, did no-tillage not have a superior SOC storage (Paustian et al. 1997); the small differences were most likely determined by tillage effects on the net primary production of C.

With continuous winter wheat in a semiarid southern U.S. latitude, Dao (1998) found a greater SOC storage in no-tillage than in moldboard tillage. Moreover, SOC storage with no-tillage in a 20 cm (7.9 in) depth was increased as available wheat residue increased, but SOC storage in the moldboard system was not sensitive to the amount of wheat residue returned. Measured CO_2 flux from the soil surface during the short summer fallow period between wheat crops confirmed these different SOC storages between tillage systems.

Before this 11 year tillage system comparison, the land had been intensively tilled. Christensen et al. (1994) observed more SOC storage in no-tillage than in a sweep-blade tillage system applied to a sorghum/fallow/wheat system in New Mexico—both had been converted from a long term moldboard system without a change in cropping system. A 25% increase of stored SOC within five years indicated a short term advantage for the no-tillage and sweep-blade system over the moldboard tillage system.

In three separate 10 year trials depicting a range of thermal and moisture environments in Texas, Potter et al. (1998) found that SOC storage in the 30 cm (11.8 in) profiles were in the order of no-tillage > non moldboard tillage > moldboard tillage systems. The driest site showed a no-tillage advantage [SOC in 0–7.5 cm (0–3 in)] over a sweep system in continuous winter wheat and/or continuous sorghum. In the two warmer and wetter locations, a rotation of corn, sorghum, winter wheat or cotton, and corn was managed in a bedded culture. In a 16 year field trial consisting of four year sequences of continuous cotton and corn, Salinas-Garcia et al. (1997) observed SOC storage with no-tillage > a disk-based system > a chisel-based system > a moldboard system. All systems except no-tillage had many secondary tillage operations in a bedded culture. Annualized C return in net primary production was at least 25% less in the no-tillage than in the other systems (Potter et al. 1998).

No-tillage stored more SOC in 20 cm (7.9 in) soil depths than a disk-based system in five different cropping systems designed to provide a net primary production ranging from 0.35–0.88 years in one cycle of the cropping system (Franzluebbers et al. 1998); although C input was less in the no-tillage system, the fraction in SOC storage was greater than in the disk-based system.

Although most wheat/fallow or sorghum/fallow field trials in semiarid to arid environments show negative SOC storages, the SOC storages rank as no-tillage > non moldboard tillage and > moldboard tillage. Primary tillage with a disk or sweep provided a SOC storage superior to a moldboard-based system in a wheat/fallow system (Allmaras et al. 1998; Rasmussen et al. 1998a), yet SOC storage in the moldboard system was still declining after more than 30 years of cropland culture.

In an adjacent field trial with wheat-pea, Rasmussen et al. (1998a) reported an aggrading SOC with the non moldboard system but a continued decline with the moldboard system. Lamb et al. (1985) showed that 12 years of wheat/fallow decreased SOC storage by 4%, 14%, and 16% for no-tillage, sweep-tillage, and moldboard tillage, respectively, when native grassland was converted to cropland. Campbell et al. (1996) found that sweep, tine, and shovel-type tillages provided less SOC storage than no-tillage in both continuous wheat and wheat/fallow systems. Over the 11 year period, there were positive SOC storages with non moldboard tillages in the continuous wheat and no-tillage in both continuous wheat and wheat/fallow. Similarly, greater SOC storages in no-tillage compared to non moldboard tillage are shown for numerous long term field trials in the Canadian Prairies (Janzen et al. 1998). Peterson et al. (1998) noted smaller SOC storage losses in no-tillage versus non moldboard tillage in the Great Plains for wheat or sorghum/fallow, continuous wheat or sorghum, and some wheat/fallow/sorghum cropping systems. Differences in net primary production can also modify the relative SOC storage in these non moldboard tillage systems.

A very detailed long term field trial in western Nebraska (Doran et al. 1998; Kessavalou et al. 1998) measured SOC losses after conversion of a grassland site to wheat/fallow. Measured SOC storage and CO_2 flux both indicated SOC loss for no-tillage was < the sweep-based system and < moldboard system. Changes of SOC in the 0–122 cm (0–48 in) layer were proportional to those in the upper 30 cm (11.8 in), but were larger. Although the sweep-based system had at least 20% less net primary production than either the no-tillage or moldboard system (Lyon et al. 1998), SOC storage losses were not as great as in the moldboard system. A similar effect of tillage systems (moldboard vs sweep) on SOC storage in a 60 cm profile was shown for wheat/fallow in Oregon (R.R. Allmaras et al. n.p.).

In the subhumid climates with corn/soybean cropping systems, most field trials included the moldboard system because it has been the traditional system for cropland management. In twelve years of tillage system comparisons with continuous corn, the no-tillage and chisel systems accumulated SOC in the 30 cm (11.8 in) soil layer relative to the moldboard system (Karlen et al. 1994). Carbon return from net primary production was nearly the same for all three tillage systems. Long term tillage comparisons in forest derived soil in Ohio indicated greater SOC storage (0–30 cm) (0–11.8 in) with no-tillage compared to moldboard tillage in continuous corn and a corn/soybean sequence (Lal et al. 1994; Dick and Durkalski 1997). Lal et al. (1994) observed more SOC storage [0–15

cm (0–5.9 in)] in the chisel system than the moldboard based system after seven years of continuous corn comparison, but in the corn/soybean sequence, the chisel system stored more SOC than either the no-tillage or the moldboard tillage. Balesdent et al. (1990) showed that no-tillage and tine tillage stored nearly similar amounts of SOC in continuous corn; moldboard tillage had at least 30% less SOC storage in the [0–30 cm (0–11.8 in)] layer than the two other systems.

In Minnesota, during a 15 year test of four soybean and 11 corn crops, no-tillage, ridge tillage (ridge position), spring disk, and fall chisel systems accumulated 10.3, 7.6, 7.3, 5.5 Mg C ha⁻¹ (4.2, 3.1, 3.0, 2.2 t ac⁻¹), respectively, more than the 95.6 Mg C ha⁻¹ (38.7 t ac⁻¹) storage in the moldboard system in the upper 23 cm layer (9.1 in) of a Nicollet clay loam (R.R. Allmaras n.p.). SOC storage in the interrow position of the ridge tillage was nearly the same as in the moldboard, and it is likely that SOC in the moldboard treatment remained unchanged because it was the only tillage system not changed for the test. An adjacent test in continuous soybean, continuous corn, and corn/soybean over 14 years showed SOC storage in the 0–45 cm (0–19 in) soil depth and ranked chisel = no-tillage but > moldboard tillage (R.R. Allmaras n.p.).

After 11 years of no-tillage comparison with a disk/chisel-based system in three cropping systems (continuous soybean, or sorghum, and soybean/sorghum sequence) in two soils of eastern Kansas, no-tillage was found to store the most SOC in the 0–30-cm layer (0–11.8 in). SOC storage in both tillage systems increased as sorghum frequency increased and more crop residue was produced (Havlin et al. 1990).

Prior to 1920, many croplands in the southeastern U.S. were severely devastated by SOC losses and soil erosion associated with clean tillage (i.e., frequent use of the moldboard plow) for cotton production, but changes in crop production practices since 1920 have begun a restoration of SOC and soil productivity (Bruce and Langdale 1997). Long term field studies, with cropping systems to facilitate net primary production throughout the summer and winter, have shown that no-tillage or infrequent tillage with chisels, disks, and cultivators can provide as much as 20 kg C ha⁻¹ yr-1 (17.8 lb ac⁻¹ yr⁻¹) SOC storage (Bruce and Langdale 1997; Hunt et al. 1996). Double cropping and cover cropping systems are currently used to maximize the annualized time for net primary production. Corn,

sorghum, and small grains, crops that produce more crop residue with more resistance to decomposition, are also replacing soybeans and cotton. However, there is now a significant use of a rye (*Secale cereale* L) cover crop and use of strip tillage in cotton production.

In a 20 year field trial in Kentucky, using continuous corn and a winter cover crop of rye, Ismail et al. (1994) found SOC storage [0–30 cm(11.8 in)] in the no-tillage system to steadily increase to a higher level than in the 50 year bluegrass sod, while SOC storage in the moldboard system dropped early in the test but was ultimately restored to its original level in bluegrass sod. During the last nine years of this field trial, the characteristically smaller SOC accumulation below 5 cm (1.97 in) steadily changed so that SOC storage in the 5–30 cm (2–11.8 in) layer is nearly the same in the two tillage systems.

Adoption of Conservation Tillage Systems

Moldboard plowing for primary tillage dominated during the 1950 to 1960 era, and conservation tillage was used on only 15–25% of U.S. cropland in 1980 (Christensen and Magleby 1983). Conservation tillage was considered merely the alternative to moldboard tillage because, at the time, there was no criteria related to crop residue cover on the soil surface. Larson and Osborne (1982) also showed conservation tillage to be 2.3% of harvested croplands nationwide in 1965 with an increase to only 16% in 1979. Research reports of the 1970 era suggest that sweep tillage was replacing moldboard tillage in the semiarid wheat lands (Allmaras et al. 1998). A comprehensive tabulation of tillage systems adoption in 1993 (ERS 1994) shows a significant

Table 4. Adoption of tillage planting systems for 1993 planting of wheat[a] (adopted from Allmaras et al. 1998).

| Tillage system[d] | Winter wheat[b] | | Spring wheat and Durum[c] | |
	Planted wheat[e]	Surface cover	Planted wheat[e]	Surface cover
	%[f]			
Conv. w/mbd	6 (0–36)	2 (1–2)	8 (3–35)	3 (2–3)
Conv. w/o mbd	76 (44–85)	13 (9–18)	56 (43–78)	16 (12–18)
Mulch-till	14 (4–25)	39 (35–45)	27 (17–36)	42 (35–46)
No-till	4 (0–28)	54 (35–72)	7 (3–21)	61 (61–72)

[a] Adapted from ERS 1994.
[b] States included are: CO, ID, IL, KS, MO, MT, NE, OH, OK, OR, SD, TX, WA.
[c] States included are: MN, MT, ND, SD.
[d] Conv. w/mbd uses the moldboard plow for primary tillage; conv. w/o mbd uses a disk, chisel, or sweep for primary tillage; conv. w/mbd and conv. w/o mbd have less than 30% surface cover after planting; mulch-till has a full-width till between harvest and planting; no-till has no tillage before planting; no-till and mulch-till have 30% or greater surface cover after planting.
[e] Percentage of planted wheat type.
[f] Mean (range) differences among states generates the range shown in parentheses.

Table 5. Adoption of tillage planting systems for a 1993 planting of soybean and corn[a] (adopted from Allmaras et al. 1998).

| Tillage system[d] | Soybean[b] | | Corn[c] | |
	Planted soybean[e]	Surface cover	Planted corn[e]	Surface cover
	%[f]			
Conv. w/mbd	8 (0–25)	3 (2–3)	9 (1–39)	2 (1–3)
Conv. w/o mbd	44 (34–82)	16 (8–20)	49 (35–60)	17 (14–19)
Mulch-till	25 (7–44)	40 (38–43)	24 (12–34)	38 (37–41)
Ridge-till	1 (0–3)	56 (56)	3 (0–17)	51 (34–53)
No-till	22 (6–38)	71 (69–75)	15 (2–27)	66 (59–76)

[a] Adapted from ERS 1994.
[b] States included are: AR, IL, IN, IA, MN, MO, NE, OH.
[c] States included are: IL, IN, IA, MI, MN, MO, NE, OH, SD, WI.
[d] Conv. w/mbd uses the moldboard plow for primary tillage; conv. w/o mbd uses a disk, chisel, or sweep for primary tillage; conv. w/mbd and conv. w/o mbd have less than 30% surface cover after planting; mulch-till has a full-width till between harvest and planting; no-till has no tillage before planting; no-till and mulch-till have 30% or greater surface cover after planting.
[e] Percentage of planted crop.
[f] Mean (range) differences among states generates the range shown in parentheses.

shift away from moldboard plow systems (Tables 4 and 5).

In the Economic Research Service (ERS) (1994) tabulation of tillage adoption (the Cropping Practices Survey), five tillage systems were defined; two were conventional and three were conservation. The three conservation systems (no-till, ridge till, and mulch till) had more than 30% surface cover with crop residue at planting; the two conventional systems—conventional without moldboard (conv. w/o mbd) and conventional with moldboard (conv. w/mbd) both had less than 30% cover. The use of the moldboard plow as a primary tillage was identified. A moldboard plow could not have been used in the conservation systems.

The no-till system has no disturbance after harvest until the next planting, except for a nutrient injection; planting was accomplished in a narrow seedbed or strip with sweeps, row cleaners, coulters, in-row chisels, rototillers, or disk openers, and there may be cultivation after planting. The ridge till system had no disturbance after harvest until planting except for nutrient injection; planting was completed in a seedbed prepared on ridges using sweeps, disk openers, coulters, and ridge cleaners. Residue cleared away from the rows at planting was then moved back into the ridges by cultivation during plant canopy closure. The fast growing strip till fits into the no-till class but can also be considered as a modified ridge till. Primary tillage tools used in the mulch till system are disks, chisels, sweeps, or cultivator shovels, but not a moldboard plow, and there is usually no more than one secondary tillage before planting. The Cropping Practices Survey that tracked the identity of the primary tillage tool was discontinued in 1995, but it is needed to continue this type of analysis.

The Crop Residue Management System (ERS 1994) is similar to the Cropping Practices Survey regarding the three conservation tillage systems. It distinguishes the two conventional systems based upon surface residue cover rather than the primary tillage tool used as: 1.) reduced tillage with 15–30% surface cover, and 2.) conventional tillage with less than 15% surface cover. In neither of the two non conservation tillage systems is moldboard tillage distinguished, although the presence of moldboard tillage as a primary tillage in the reduced tillage system (15–30% cover) would be rare unless an excessively large amount of crop residue existed after harvest and a shank-type secondary tillage moved residue back to the surface.

Summations of land planted in conventional systems without moldboard, mulch till, ridge till and no-till systems (94%, 92%, 92%, and 91%, respectively for winter wheat, spring wheat, soybean, and corn) indicate placement of crop residue on the surface no deeper than 10 cm (4.2 in). The complement (6%, 8%, 8%, and 9%, respectively) indicates a small percentage of deep crop residue burial using moldboard tillage. Distinctions between conventional systems with moldboard (conv. w/mbd) and without moldboard (conv. w/o mbd) are necessary for assessing a C sink potential because of the potential for different C loss. For each of the four crops (Tables 4 and 5), the mean surface residue cover at planting time was also estimated (ERS 1994).

Tillage rotation can provide SOC storage with conservation benefits when the moldboard system is excluded. Nearly all crop residue is buried below 15 cm (5.9 in) in the moldboard system compared to systems using chisel, disk, or sweeps for primary tillage (Staricka et al. 1991; Allmaras et al. 1996a), which explains the relatively small surface cover in the conv. w/mbd tillage system (Tables 4 and 5).

Annually repeated moldboard tillage buries the recent crop residue and returns the last year's decomposed residue to the surface, but repeated use of other primary tillages buries recent crop residue in the same zone as the last year's crop residue. The amount left on the surface depends on the tillage tool, amount of crop residue, and the number of passes (Allmaras et al. 1996a). Aggregate turnover, due to rupturing and reforming during tillage, is actually less in the moldboard system than in systems where traffic com-

paction and secondary tillage are nearly as deep as primary tillage, and crop residue burial is not below the depth of secondary tillage (Staricka et al. 1992).

A more intense anaerobic environment in the moldboard system, when fresh crop residue is incorporated (Staricka et al. 1991; Allmaras et al. 1996a), indicates that tillage rotation is compatible among all systems except conv. w/mbd when SOC storage is the major objective. McCarty et al. (1998) noted a 38% increase in SOC in the 0–2.5 cm (0–1 in) layer and a 7% loss in SOC in the 2.5–20 cm (1–7.9 in) layer three years after conversion from moldboard tillage to no-tillage. Pierce et al. (1994) observed that SOC storage in a long term no-tillage system was not seriously reduced when measured four years after one tillage with a moldboard plow.

Two possible mechanisms for less decomposition of the biomass (that was previously accumulated and partially decomposed under no-tillage) after it was placed in the anaerobic environment with a moldboard plow are: 1.) a smaller CO_2 production because some decomposition had already occurred, and 2.) prior fungal colonization of the biomass. Fungal compared to bacterial decomposition produces more recalcitrant decomposition products—fungal decomposition is also characteristically more active at shallow depths (Holland and Coleman 1987).

Tillage systems used for sorghum were not tabulated by the ERS (1994) system. The Crop Residue Management System, however, noted 68% of planted sorghum had less than 30% surface cover while cover for planted corn and winter wheat was 64% each (ERS 1994). In the Cropping Practices System, the two < 30%

Table 6. Adopted conservation tillage systems in 10 southeastern states (1998)*.

Crop	Conservation Tillage[†] NT	RT	MT	Conventional Tillage[†] 15 - 30%	< 15%
			% of Planted Crop		
Corn (fs)[‡]	32	2	12	17	36
Cotton	10	3	4	16	67
Grain Sorghum (fs)	10	2	11	28	48
Small Grain (sp)	8	0	2	14	76
Soybean (fs)	20	1	7	21	51
Other Crops	2	0	0	16	78
Corn (dc)	48	0	13	19	20
Grain Sorghum (dc)	32	0	16	37	22
Soybean (dc)	59	0	7	15	18
Small Grain (wn)	17	0	15	23	45

* Southeastern states: AL, AR, FL, Ga, KY, MS, NC, SC, TN, VA; source is 1998 Crop Residue Management survey, Conservation Technology Information Center.
† Conservation tillage systems with > 30% surface cover at planting are no-till (NT), ridge-till (RT), and mulch-till (MT); conventional systems have 15 to 30, or < 15% surface cover at planting of the listed crop.
‡ fs is full season; dc is double cropping; wn are fall planted small grain; and sp are spring planted small grain.

cover categories were 58% and 82% of planted corn and wheat, respectively. Similar percentages of < 30% of surface cover for sorghum, corn and winter wheat in the two survey systems suggest that the moldboard system could have been used at about the same level of < 8% for planted sorghum in 1993.

Adoption of conservation tillage systems, with > 30% surface cover and with residue at planting, is quite different in the southeastern states (Table 6) than shown nationally for corn, soybeans, and wheat. Comparisons (not shown) between 1998 and 1993 in the Crop Residue Management survey show minor changes since the 1993 survey (Tables 4 and 5). There is an unusually high percentage of crops planted into crop residue cover with < 15% while the planted crop in the 15–30% category is somewhat lower than the conv. w/o mbd category (Tables 4 and 5). Planted cotton and southern states soybean in the conv. w/mbd tillage system in 1993 was always less than 10% (ERS 1994). This shows a direct relationship to accelerated residue decompositions when there is any form of tillage. Another indicator is the smaller amount of cropland in the mulch till category compared to that shown in Tables 4 and 5, even one full-width tillage is enough to reduce residue cover below 30%.

Because of climatic conditions in the southeastern states, there can be a continuity of net primary production without a prolonged interruption due to frost as in the northern states. A combination of cover crop, double crop, no-tillage, and infrequent use of non moldboard tillage has initiated and expanded the C sink. Corn (fs), cotton, soybean (fs), soybean (dc), and small grain (wn) make up 80% of the cropland (Table 6). Along with the no-tillage practice, these crops can elongate the period for net primary production in the warm season and when a cover crop is photosynthesizing during the cool season. Grain sorghum (fs and dc) has also been included in the crop rotation. Fortunately, it provides a crop residue more resistant to decomposition.

A Positive Carbon Sink in U.S. Croplands

Current levels of crop residue (net primary production) return, the relative SOC storage controlled by tillage systems, and changes in tillage system practice away from moldboard plowing in U.S. croplands have collectively shifted cropland from a C source to a C sink sometime in the last 15 years. This model

for assessing the potential for a C sink is simple and direct with regard to field operations, and therefore, has a distinct advantage for functionally interpreting SOC storage relative to systems of tillage and crop residue handling. Other approaches to quantifying the C sink in Canadian and U.S. cropland agriculture have also been developed.

One of the first and most comprehensive schemes predicted a positive C sink in year 2020 when no-tillage was expected on 76% or more of the cultivated cropland (Kern and Johnson 1993). The scheme used tillage system adoption data, expected production of crop residues, a detailed national SOC data base, and an assessment of SOC storage produced by tillage systems. However, Kern and Johnson assumed no differential of SOC storage between "minimum" (including ridge and mulch tillage), tillage and conventional (moldboard) tillage. They considered a difference of SOC storage only between no-tillage and all other forms of tillage, and assumed little or no tillage control over SOC differences below 8 cm (3.2 in). The database they used for adoption of tillage systems did not distinguish moldboard, and therefore, no difference of SOC storage was noted between moldboard and other systems that did not include no-tillage in the field comparisons used for standardizing SOC storage. Projected SOC storage (Kern and Johnson 1993) for designated climatic areas were used later (Patwardhan et al. 1997) to calibrate the CENTURY soil carbon model and to project SOC storage based on tillage/crop/rotation scenarios.

More recently Donigian et al. (1997) used CENTURY along with agricultural practices and production databases to simulate impacts of crops, rotation, and tillage on SOC storage changes over time within climatic zones. For the study area (Corn Belt, Great Lakes Region, and eastern Great Plains), projected SOC storage with reduced tillage (non moldboard systems that had an annual tillage) was about 15% higher than in the moldboard, and for no-tillage it was often 50% higher after only a 20 year period (1990 to 2010). Although the soil environment related to tillage system and crop residue management was not fully parameterized into the CENTURY model, Donigian et al. (1997) concluded that U.S. croplands had achieved a C sink during the 1970 to 1990 period.

A C sink was also shown by Patwardhan et al. (1997) for the period from 1970 to 1990 during calibration of CEN-

TURY. Predicted SOC storage during 1990 to 2010 by Donigian et al. (1997) appeared excessive when compared to an analyses of many long term tillage experiments by Paustian et al. (1997), wherein the largest SOC in no-tillage was no more than 20% higher than in a paired moldboard system. Our comparisons among the no-tillage, non moldboard, and moldboard systems also confirm the excessive no-tillage storages of SOC in the Donigian et al. (1997) study.

Appraisals were also made for a C sink in Canadian cropland (Janzen et al. 1997; Izaurralde et al. 1997). Most Canadian cropland is viewed as an ecosystem that replaced natural grassland. When grassland was converted to cropland there were many simultaneous changes; for example, harvest of biomass and nutrients, lower natural partition of net primary production into roots of cropland vs. grassland species, longer wet periods in cropland for decomposition, tillage systems, and some natural resistance to decomposition. Nevertheless, there are several approaches that suggest a recent C sink in cropland. Repeated sampling in long term cropping sites show that the rates of rapid SOC loss early in cropland history have changed, and SOC storages are now steady or increased only after minor changes in crop sequence, especially changes away from fallow in semiarid croplands (Janzen et al. 1997).

The CENTURY simulation model indicates about a 20% loss of SOC in the 0–30 cm (0–0.98 ft) layer from 1910 to 1990 but a near zero change since 1990 (Smith et al. 1997). Two significant changes are less summer fallow and increased no-tillage to replace stubble mulch in semiarid croplands, and reduced use of moldboard tillage in more humid climates (Janzen et al. 1997; Izaurralde et al. 1997).

Jointly Managing the C Sink and Conservation of Soil and Water

Realization of a C sink and an associated C credit will be more likely if one can show an array of other benefits to production and conservation, including environmental quality. This is a system of long term land management with many interrelated processes, hence the need for a simple and process oriented (mechanistic) model to guide and improve tillage and crop residue management for a reliable C sink, while at the same time indicating impacts on soil and water conservation.

Many improvements and updates are needed to more accurately assess C avail-

able from net primary production. The harvest index (HI) in Table 2 conservatively estimates crop residue available to build a C sink because a significant portion of grain and oil seeds are produced under a stress (water and/or nutrient) and a reduced HI. The HI of wheat in a wheat/fallow system is usually larger than observed in continuous wheat because of late season water stress in continuous wheat (Peterson et al. 1998).

More field measured HI for dry matter can assist with a site- or region-specific estimate of biomass available to build the C sink with different crops. Use of a HI for nutrients can also assess fertilizer needs in the same way that a HI for dry matter displays the burden of C removal placed upon harvested cropland. This approach has been used to compute nutrient mass balances of N, P, and K for corn, soybean, and wheat production (NAS 1993; ERS 1994).

The C return estimates of Table 3 were based upon a root:shoot ratio = 0.2 and the listed HI. Root dry matter and rhizodeposition resulting from net primary production for the whole growing season under field conditions of tillage, crop residue history regarding amount and position, climate, cultivar differences, and fertilization variations has not often been measured with such detail as that by Balesdent and Balabane (1992). This detail is required to more accurately assess potential to build the C sink. One serious problem is root biomass measurement at late stages of vegetative or early reproductive growth and failure to track subsequent root and shoot biomass increase during a period when HI may change markedly.

When stover and grain is harvested, the root:shoot ratio assumes more importance because the structurally intact root tissue is more recalcitrant than shoot tissue (Balesdent and Balabane 1996). To account for such situations (e.g., when corn stover is removed for the biofuels industry), an appropriate HI must be used with a root:shoot ratio adjusted for root relative to shoot recalcitrance.

The Cropping Practices Survey (ERS 1994) uses statewide data banks (Tables 4 and 5) and computes many of the same parameters sought to estimate runoff and soil erosion by water under the control of tillage and residue management. Grain yields were used to estimate crop mass residue after harvest. The sequence of tillage operations (tillage tool), the number of field operations, and the type of seeder were all used in the Cropping Practices Survey to estimate the reduction of original surface residue and the surface area covered, just as for the surface cover component in the C (cropping) factor of the RUSLE equation (Renard et al. 1991). Associated with each tillage operation (with the designated tillage tool) an estimate of surface cover, surface random roughness, and residue buried above 10 cm (4.2 in) can be made (Allmaras et al. 1998). The information for each and every tillage operation during the harvest-to-planting period can be used to estimate water erosion (Renard et al. 1991) and wind erosion (Skidmore 1994).

Changes in soil water relations and rooting environment can be predicted by SOC contents and other constituent properties. Predicted critical points in the soil water retention characteristic (field capacity and wilting point) use SOC content (Kern 1995; Kay et al. 1997). Restrictions to rooting environment based on available water, soil porosity, and soil strength can be predicted using SOC content in pedotransfer functions (Kay et al. 1997). Kay (1997) also reviewed specific SOC impacts on soil structure and associated links to soil water and soil strength.

Water infiltration responses to tillage and crop residue management in the five tillage categories (Tables 4 and 5) are more difficult to estimate than soil erosion estimates. Yet infiltration is a primary process involved in runoff, erosion, and soil water storage for subsequent transpiration and net primary production. Microbial activity and biomass during crop residue decomposition produce polysaccharides and other humic substances that actively produce water stable aggregates. When crop residues are buried above 10 cm (4.2 in) or maintained on the surface, as in the four categories other than the conv. w/mbd, they can produce water stable aggregates at the surface to prevent soil crust/seal formation (Bruce et al. 1992; Allmaras et al. 1996b). There is a window of time between harvests when these ephemeral water stable aggregates are formed; this window of time depends on soil temperature and moisture as suggested by the modeled decomposition rate of crop residue (Douglas and Rickman 1992).

Infiltration responses to tillage and traffic also depend on soil texture, antecedent moisture, water flow properties within the tilled layer below the near surface layers (e.g., those controlled by traffic induced compaction), and surface roughness (Bradford and Huang 1992). A change in saturated hydraulic conductivity is a sensitive indicator of infiltration response to kinetic energy of rainfall and the soil resistance to such energy inputs (Allmaras et al. 1996b; Nearing et al. 1996). Soil organic carbon is an important input variable for predicting saturated hydraulic conductivity (McKeague et al. 1982).

The Cropping Practices Survey (ERS 1994) can facilitate a search for regional factors that encourage or suppress tillage practices conducive to developing the C sink, as well as soil and water conservation. The range for use of the conv. w/o mbd among states (Tables 4 and 5) is small when normalized by the mean value—this is true for all four crops. A moderate conversion of these systems to no-tillage appears not to be regionally sensitive. Given that no-tillage is the best system for a C sink, the low adoption of corn in Minnesota and Wisconsin and soybeans in Minnesota and Nebraska distinguishes regions where negative factors must be identified in order to increase the C sink. One possible approach is to increase the use of strip tillage or ridge tillage to avoid or prevent random traffic and associated poor internal drainage. The conv. w/mbd system is still used at rates higher than 10% for planting soybeans in Indiana, Ohio, and Minnesota and for planting corn in Michigan, Minnesota, Ohio, and Wisconsin—conversion to a conv. w/o mbd would provide a major C sink improvement.

No-tillage systems for planted winter wheat are at 25% in Missouri, Illinois, and Ohio, but are below 6% in most states in the semiarid west. Fallow combined at least once with winter wheat in a three year rotation ranges from 31% in Texas, to 88%, 95%, and 98% in Colorado, Montana, and Oregan, respectively. The conv. w/mbd system ranges >10% of the seeded winter wheat in Idaho, Oregon, and Oklahoma. These tillage adoptions, as detailed in the Cropping Practices Survey, suggest that no-tillage without fallow is needed in winter wheat production to improve the C sink, as proposed by Peterson et al. (1998). Combining no-tillage with continuous cropping in the semiarid Canadian wheatlands has recently contributed to a positive C sink in Canada (Janzen et al. 1997).

The use of the conv. w/mbd system for spring wheat (Table 4) varies greatly among states, with Minnesota much higher (35%) compared to South Dakota, Montana, and North Dakota. Much of the spring wheat land of Minnesota and South Dakota is in rotation with

rowcrops, while in North Dakota and Montana, especially, wheat land is fallow once in three years. Changes to enhance the C sink in the spring wheat belt are, therefore, not similar to those expected in the winter wheat lands.

Burial patterns of crop residue associated with the tillage tool used in the five categories of tillage systems (Tables 4 and 5) can be used to better manage fertilizer and herbicide interactions with the residue (Allmaras et al. 1996a) in the Corn Belt and Great Plains. In the conv. w/mbd system, the fresh crop residue at harvest and most of the root tissue is incorporated below 10 cm (4.2 in) while the much reduced mass of crop residue after a year of decomposition is above 10 cm (4.2 in). In all other categories (Tables 4 and 5), the crop residue is either on the surface or buried above 10 cm (4.2 in).

Longevity without degradation and potential for movement (runoff or leaching) of incorporated herbicide (usually no deeper than 7 cm) is less likely in systems other than conv. w/mbd because of intimate contact with fresh crop residue (Allmaras et al. 1996a). In these non moldboard systems, herbicide placement must avoid macropore conduits, which are generally more prevalent. Green et al. (1995) indicate that nitrogen fertilizers should not have intimate contact with crop residue. Band placement below 10 cm (4.2 in) may be a best management practice (BMP) for the non moldboard system but not in moldboard systems. In fact, broadcast after primary tillage may be best in moldboard systems to separate crop residue from N fertilizers. These considerations can help achieve simultaneous environmental quality and an enlarged C sink.

Conclusion

Storage of soil organic carbon (SOC) in cropland soils depends on the amount and placement of the crop residues returned and the associated tillage system. To determine if there is a net gain or loss of organic matter in the major croplands of the U.S. for production of wheat, corn, soybeans, and sorghum, these were examined for: a.) historic trends of C return in crop residues, b.) comparative SOC storage among tillage systems (no-tillage, non moldboard tillage, moldboard tillage), and c.) adoption trends for tillage/planting systems. Because sig-

nificantly less SOC storage was found in the moldboard system compared to the other two systems, and the shift from dominant moldboard primary tillage in the 1960 to 1970 era to a use on less than 8% of planted cropland in 1993, SOC storage has shifted from a C source to a C sink. As farmers gradually develop no-tillage systems, the C sink will steadily increase.

The model used in the assessment is linked to the primary and secondary tillage tools and their control over crop residue placement—it is also sensitive to regional differences in tillage and cropping systems. The model can also be used to project soil and water conservation, production, and environmental quality benefits as needed to support a C credit program.

The model has not been developed sufficiently, at this time, to estimate the rate of C sink or source development based on such factors as prior land use, tillage, climate, soil properties, crop residue return, use of fertilizers, and use of pest control chemicals. Several studies indicate that when tillage systems store more SOC in the traditional plow layer [30 cm (0.98 ft) layer], they also store more in the subsoil. Continued use of this model requires that tillage adoption surveys use tillage tools rather than surface residue covers as indicators of tillage systems to assess C sequestration and other such benefits as soil and water conservation.

An increased and sustained C sink is necessary for a C credit. A major gain can occur as cropland agriculture reduces secondary tillage after primary tillage with non moldboard tillage tools and moves closer to no-tillage. These adoption trends are accomplished by a systematic change in the tillage and planting tools. Further analysis of adoption trends, based on tillage tools and the use of associated field operations-based systems, will guide quantification of the C sink and associated soil and water benefits.

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